Supercritical Steam power cycle for Line-Focus Solar Power Plants

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Abstract

The supercritical Rankine power cycle offers a net improvement in plant efficiency compared with a subcritical Rankine cycle. For fossil power plants the minimum supercritical steam turbine size is about 450 MW. A recent study between Sandia National Laboratories and Siemens Energy, Inc., published on March 2013, confirmed the feasibility of adapting the Siemens turbine SST-900 for supercritical steam in concentrated solar power plants, with a live steam conditions 230-260 bar and output range between 140-200 MWe. In this context, this analysis is focused on integrating a line-focus solar field with a supercritical Rankine power cycle. For this purpose two heat transfer fluids were assessed: direct steam generation and molten salt Hitec XL.

To isolate solar field from high pressure supercritical water power cycle, an intermediate heat exchanger was installed between linear solar collectors and balance of plant. Due to receiver selective coating temperature limitations, turbine inlet temperature was fixed 550ºC. The design-point conditions were 550ºC and 260 bar at turbine inlet, and 165 MWe Gross power output. Plant performance was assessed at design-point in the supercritical power plant (between 43-45% net plant efficiency depending on balance of plant configuration), and in the subcritical plant configuration (~40% net plant efficiency).

Regarding the balance of plant configuration, direct reheating was adopted as the optimum solution to avoid any intermediate heat exchanger. One direct reheating stage between high pressure turbine and intermediate pressure turbine is the common practice; however, General Electric ultrasupercritical (350 bar) fossil power plants also considered doubled-reheat applications. In this study were analyzed heat balances with single-reheat, double-reheat and even three reheating stages. In all cases were adopted the proper reheating solar field configurations to limit solar collectors pressure drops.

As main conclusion, it was confirmed net plant efficiency improvements in supercritical Rankine line-focus (parabolic or linear Fresnel) solar plant configurations are mainly due to the following two reasons: higher number of feed-water preheaters (up to seven) delivering hotter water at solar field inlet, and two or even three direct reheating stages (550ºC reheating temperature) in high or intermediate pressure turbines. However, the turbine manufacturer should confirm the equipment constrains regarding reheating stages and number of steam extractions to feed-water heaters.

Keywords: Supercritical steam solar power plant, Supercritical Rankine power cycle, Direct Steam Generation, Molten salt, Line-focus solar collector, Parabolic Trough, Linear Fresnel.

1. Introduction

Solar thermal power plants generate carbon dioxide-free electricity by the transformation of solar light radiation into thermal energy. Despite, solar power plants not consume any fossil fuel, the target is to minimize plant capital investment cost reducing the equipments volume, complexity and components manufacturing secondary environmental impacts. The power plant efficiency is the selected key parameter for measuring power plant design-point performance and limited by Carnot principle.

Subcritical water Rankine cycles are the most adopted power generation solution in actual Concentrated Solar Power plants (CSP), providing plant efficiencies up to 38-40%, see Table 7 to 10. However, thanks to the synergies with the fossil power plants, supercriticial turbines, operating above 22.1 MPa and 374.1ºC water critical point, are being studied as an alternative to increase plant efficiency.

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In this paper it is demonstrated how the supercritical Rankine power cycles offers 43- 45% net efficiency at design-point (550ºC and 260 bar at turbine inlet), see Tables 7 to 10. With live steam pressure at turbine inlet above water critical point, turbine pressure levels and number of turbines extractions could be increased, hence solar field (SF) feed-water inlet temperature is enhanced. We considered in the innovative supercritical Rankine cycle proposed in this paper seven feed-water pre-heaters, as stated in [1], and five feed-water pre-heaters in the subcritical Rankine cycle. A more detailed assignment of the turbine pressure levels are detailed in [2].

Supercritical water provides an important physical property key advantage, the higher supercritical water density in comparison with steam water. With a proper steam paths and blades design turbines stages efficiencies could be improved and secondary losses reduced. A recent study between Sandia National Laboratories and Siemens [3], concludes high-speed and high pressure Siemens turbine SST-900 could be upgraded to reduce secondary losses in steam blade path and also takes the advantage of supercritical steam for an output range of 140 to 200 MWe. This turbine would be developed for short startup times, daily cycling, and rapid load changes required in solar power plants. The supercritical turbines technology foundation also relies on more sophisticated materials with better mechanical properties (T91, 347 SS, Inconel, etc) [4] already manufactured for supercritical and ultrasupercritical fossil power plants.

According to Carnot principle the plant efficiency is improved for higher live steam pressure and temperature, but temperature is limited by receivers' selective coating materials, and is fixed to 550ºC. Molten Salt (MS) Hitec XL and Direct Steam Generation (DSG) are the Heat Transfer Fluids (HTF) selected, not suffering any degradation at 550º C operating temperature.

Also two scenarios were considered in this paper for line-focus solar field design, Parabolic Trough collectors (PTC) or Linear Fresnel (LF) collectors. PTC optical efficiency is better than LF, but the flat mirrors and lack of movable joints in LF make this alternative solar collector competitive with traditional linear PTC. SF design optimization, is quantify in terms of the Unitary Power Output, as the relation between net power output and the solar field effective aperture area. The target is to maximize this parameter to reduce SF dimensions for a fixed power output. Mass flux (kg/m2 s) was also limited in main SF and in reheating SF to reduced pressure drops and obtaining a fluid velocity not producing vibration, erosion, etc inside receivers, neither in headers pipes.

Other important key issue impacting directly in plant efficiency is the number of reheating stages in High Pressure (HP) and intermediate pressure (IP) turbines. Steam reheating provides another way of optimizing plant performance, but number of reheating stages are limited by pressure drops and by turbine design. Direct ReHeating (DRH) was adopted avoiding any intermediate heat exchanger. Supercritical live steam pressure at turbine inlet (260 bar) permits to integrate one, two or even three DRH stages in the power cycle, see Fig. 3 and Fig. 4; always assuring reheating solar field pressure drops not impacts too much in power cycle, and steam quality leaving last turbine stage is above 0.9, avoiding blades damages due to water droplets.

2. Methodology

This paper is focus on assessing the design-point performance of supercritical line-focus (PTC and LF) solar power plants integrating supercritical water Rankine cycles. For this purpose, plants modeling and simulations were developed with Thermoflow 23. Water properties were calculated according to IFC-67 steam tables. MS (Hitec XL) properties were calculated with internal Thermoflow 23 tabulated data.

3. Modeling assumptions

Main calculation assumptions were summarized in Table 1 to Table 6.

Table 1. *Location and ambient conditions.*

Location:	Dagget, CA, USA.
Latitude:	34.86 º
Longitude:	-116.8 º
Hourly zone:	-8
Time:	11:30 hr
DNI:	986 W/m2
Ambient temperature:	25 ºC
Altitude:	588 m

Table 2. *Receiver parameters.*

Pipe material:	Stainless Steel
Outer diameter:	70 mm
Thickness:	4-8 mm
Internal roughness:	Ra = 0.0457 mm
Max. DSG velocity (m/s)	40-50
Max. MS velocity (m/s):	2

Table 3. *PTC solar collectors' parameters.*

Collector type:	EuroTrough II
Aperture Width:	5.77 m
Focal Length:	1.71 m
Cleanliness factor:	0.96
Optical Efficiency:	0.75
Thermal Losses:	$0.141\ \Delta T + 6.48e\text{-}9\ \Delta T^4$ (boiling superheated DSG) [5]

Table 4. *LF solar collectors' parameters.*

Collector type:	SuperNova1 (Novatec)
Aperture Area:	5.77 m
Dimensions:	1.71 m
Optical Efficiency:	0.67 (boiling); 0.647 (superheating)
Thermal losses:	$1.06\ \Delta T + 1.2e\text{-}8\ \Delta T^4$ (boiling DSG) [7]
Thermal losses:	$0.15\ \Delta T + 7.15e\text{-}9\ \Delta T^4$ (superheated DSG) [6]

Table 5. *SubCritial Balance Of Plant parameters.*

HP turbine inlet (bar):	87.7
HP turbine inlet (ºC):	550
Turbines isentropic efficiency (%):	0.85
Nº of HP stages:	2
Nº of IP stages:	3
Nº of LP stages:	4
Reheating outlet (ºC):	550
LP turbine quality:	Above 0.9
Condenser (bar):	0.08
Preheater units:	5
Deareator (bar):	6.18
Preheaters TTD (ºC):	5
Preheaters DCA (ºC):	5

Table 6. *Supercritical Balance Of Plant parameters.*

HP turbine inlet (bar):	260
HP turbine inlet (ºC):	550
Turbines isentropic efficiency (%):	0.85
Nº of HP stages:	2
Nº of IP stages:	3
Nº of LP stages:	4
Reheating outlet (ºC):	550
LP turbine quality:	Above 0.9
Condenser (bar):	0.08
Preheater units:	7
Deareator (bar):	8.5
Preheaters TTD (ºC):	5
Preheaters DCA (ºC):	5

4. Line-focus solar field with Direct Steam Generation and Subcritical Rankine power cycle (Reference Configuration)

Following the latest trend in line-focus solar power plants technology development, for the present study was adopted, as reference configuration, a solar power plant with linear collectors (PTC or LF) with DSG and a Subcritical Rankine power cycle, see Fig.1 and 2, and results summarized in Tables 7, 8, 9 and 10.

The DSG recirculation mode was selected in this analysis, and was validated in DISS researching project, and also industrial scale power plants were constructed and are operating with PTC DSG (Kimberlina project) and with LF DSG (Puerto Errado project). DSG with recirculation mode is integrated by a preheating and boiling SF delivering a 80% saturated steam quality; the steam liquid phase is separated in a tank and the vapor is superheated in other solar collectors before entering the HP turbine, for more details see Fig.1. DSG as HTF main advantages are: no environmental impact, no HTF solidification, no heat tracing required, no operating temperature either pressure limit, reduced pipe corrosion, etc.

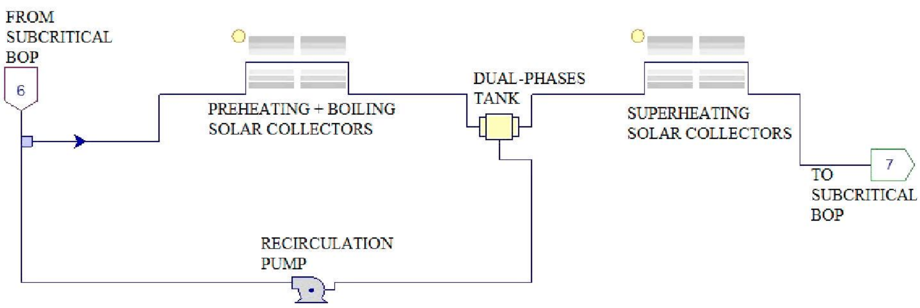

Figure 1. *Direct Steam Generation Solar Field (PTC or LF) with Recirculation mode.*

In relation to BOP, the most relevant feature is the DRH (550ºC) between HP and IP turbine. By means of the reheating plant efficiency is increased up to 40% in comparison with the solution without reheating providing only 38.4% net efficiency. Two DRH stages are considered in the reference Subcritical Rankine configuration, see Fig. 2.

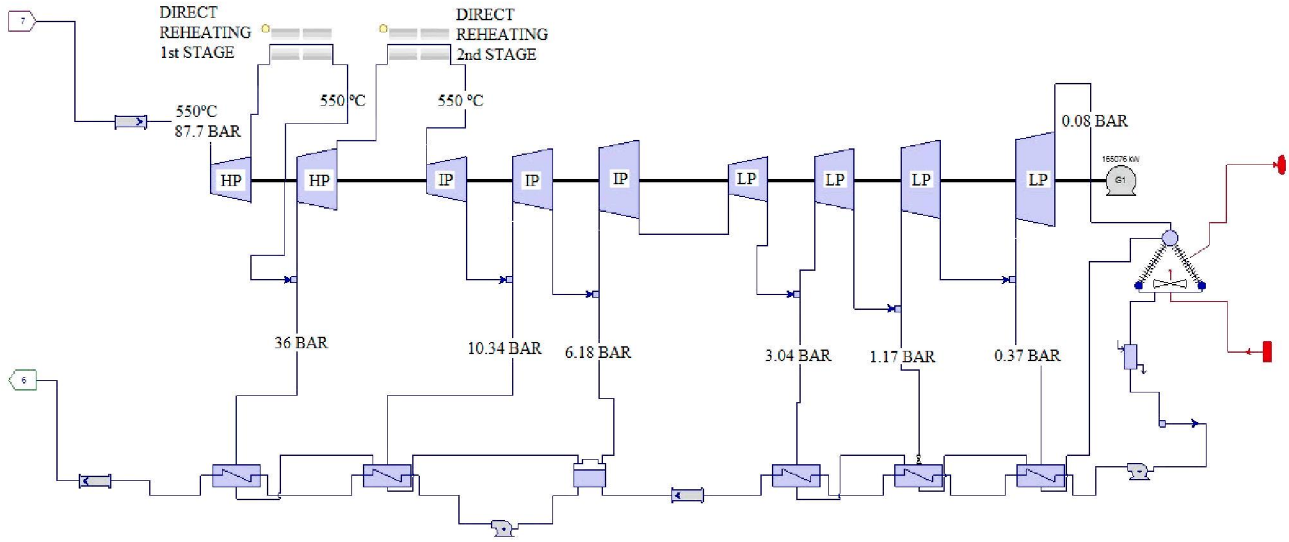

Figure 2. Subcritical Rankine power cycle with 5 preheaters and a dearator.

5. Line-focus solar field with Direct Steam Generation and Supercritical Rankine power cycle

Instead of DSG with recirculation mode (reference Configuration illustrated in Fig.1), in this study it is proposed an innovative DSG alternative, linear solar collectors operating only with steam above saturated conditions, see Fig. 3.The saturated steam is produced at plant start-up by means of an auxiliary fossil boiler connected in parallel with the solar collectors. During normal operation conditions superheated steam not condensates inside solar collectors, reducing number of auxiliary equipments (recirculation pumps, separation dual-phases tanks and simplifying control strategies), see Fig. 3.

Main challenge in this configuration is the industrial development of the steam compressors to operate under the thermodynamic conditions detailed in this study and with a high isentropic efficiency to decrease auxiliary steam compressor electrical consumptions. For this purpose SF operating pressures from 150 bar to 250 bar were simulated and results confirm higher SF steam pressures reduces steam compressor electrical consumptions. Three different materials were selected for each pressure range (Carbon Steel 100-125 bar, ferritic stainless steel T91 150-175 bar and austenitic stainless steel 347SS 200-250 bar). Maximum receiver thickness was limited to 9 mm to avoid any disturbing in heat correlations provided by experiments and validations [5] and [6]. For summarizing requirements only 150 bar SF operations conditions results are detailed in Table 7 and 8.

The main SF design and configuration is very important to minimize pressure drops along receivers and along SF headers. For this purpose it was limited the collector maximum length fixing the mass flux (kg/m2 s) limits. Other way of reducing pressure drops is to increase receiver diameter from 70 mm to 90 mm. For this reason receiver thickness was increased from 7.6 mm to 8.6 mm without considering the corrosion thickness requirements. Finally mass flux limits were: 750 kg/m2 s in 70 mm receivers and 650 kg/m2 s in 90 mm receivers.

Also to minimize pressure drops in DRH solar collectors mass flux was limit in the 1st and 2nd reheating stages up to 600 kg/m2 s and in the 3rd reheating stage up to 300 kg/m2 s.

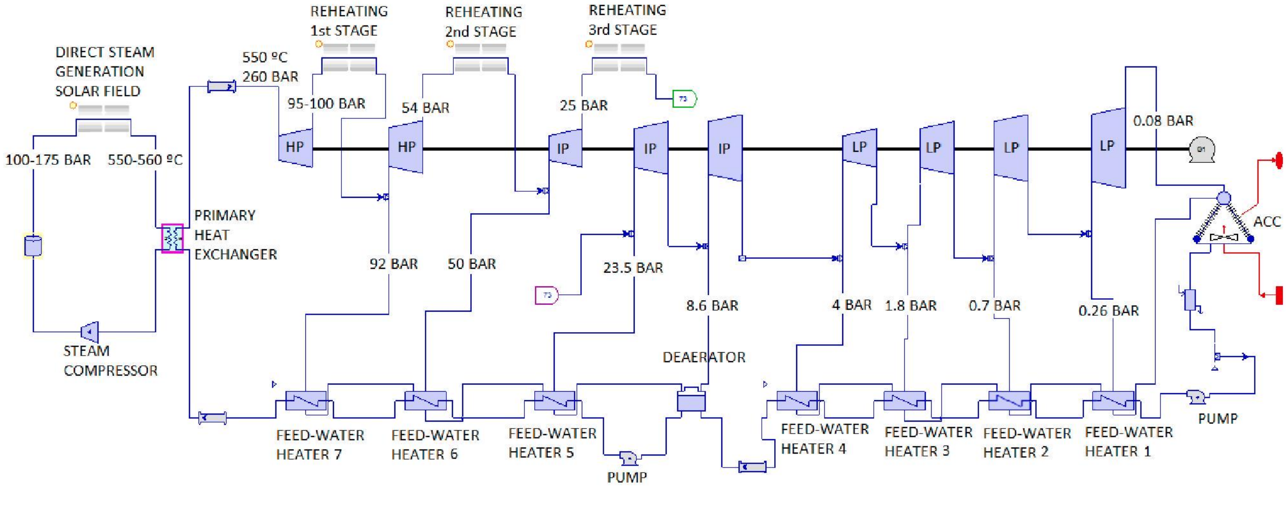

Figure 3. Direct Steam Generation Solar Field (PTC or LF) with Supercritical Steam Rankine power cycle.

As detailed in Table 7 and Table 8 it was confirmed higher net plant efficiency values are obtained with supercritical Rankine power cycles with seven feed-water pre-heaters. The plant configuration providing better efficiency is integrated by three DRH stages, however this configurations was not yet deployed neither validated in a industrial plant and is subjected to turbine manufacturers constrains confirmation. The plant configuration with only one DRH stage is the most common and also increase net plant efficiency from 40% to ~ 42.7% in supercritical Rankine cycles. Talking about the SF dimensions, the unitary power defined as the relation between net power output and SF effective aperture area, with supercritical Rankine power cycles unitary power output is increased from 0.22 to 0.23 (around 5% increment).

Table 7. Comparison between Subcritical Rankine power cycle and Supercritical Rankine power cycle design-point performance in a LF with DSG solar power plant, *(550 ºC HP inlet).*

Power cycle	**subcritical Water (reference)**	**subcritical Water (reference)**	**supercritical Water**	**supercritical Water**	**supercritical Water**	**supercritical Water**
Graphical illustration	Figs. 1, 2	Figs. 1, 2	Fig. 3	Fig. 3	Fig. 3	Fig. 3
DRH stages	2nd	1st	2nd	1st, 2nd, 3rd	1st, 2nd	2nd, 3rd
Main SF pressure (bar)	104	104.5	150	150	150	150
HP inlet pressure (bar)	87.7	87.7	260	260	260	260
Net Efficiency (%)	40.44	40.16	42.66	44.32	43.9	43.56
Unitary power (W/m2)	226.5	222.1	227	235	234.2	232.2

In Table 8 are summarized the results for PTC solar collectors. We obtained higher unitary power output values (~ 16%) due to better PTC optical performance in relation with LF collectors. However, a future cost study should conclude which is the optimum alternative. PTC and LF are two technologies under continuous industrial development processes and both alternatives should be considered.

Table 8. Comparison between Subcritical Rankine power cycle and Supercritical Rankine power cycle design-point performance in a PTC with DSG solar power plant, *(550 ºC HP inlet).*

Power cycle	**subcritical Water (reference)**	**subcritical Water (reference)**	**supercritical Water**	**supercritical Water**	**supercritical Water**	**supercritical Water**
Graphical illustration	Figs. 1, 2	Figs. 1, 2	Fig. 3	Fig. 3	Fig. 3	Fig. 3
DRH stages	2nd	1st	2nd	1st, 2nd, 3rd	1st, 2nd	2nd, 3rd
Main SF pressure (bar)	104.6	104.7	150	150	150	150
HP inlet pressure (bar)	87.7	87.7	260	260	260	260
Net Efficiency (%)	40.41	40.09	42.9	44.52	43.81	43.78
Unitary power (W/m2)	265.8	263.7	268.8	276.8	273.2	274.4

6. Molten salt line-focus solar field with supercritical water Rankine power cycle

The solar power plant configuration illustrated in Fig.4, with MS as HTF fluid in linear solar collectors (PTC or LF), is an alternative to DSG linear solar collectors. This configuration main advantage is to minimize auxiliary SF parasitic electrical consumption. MS recirculation pump consumes much lower electricity in comparison with steam compressor. HTF salt velocity is limited to 2 m/s, optimizing SF pressure drops, pipes corrosion and erosion. Hitec XL salt was selected for reducing heat tracing requirements and avoiding salt solidification inside receivers. MS other advantages are: reduced operating pressures, good heat transfer coefficient (HTC) in solar field heat exchangers, etc.

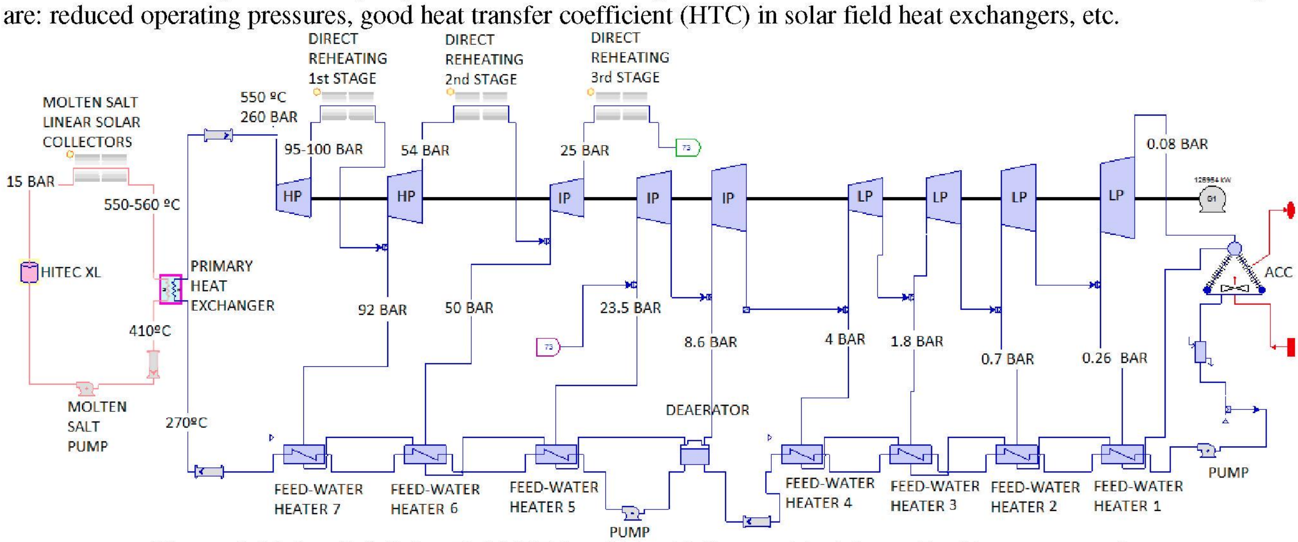

Figure 4. *Molten Salt Solar Field (PTC or LF) with Supercritical Steam Rankine power cycle.*

In Table 9 and 10 is confirmed how the net plant efficiency with MS and supercritical Rankine cycles is 3-5% better in comparison with subcritical Rankine solar plants. Also if we compared the results obtained with DSG and supercritical Rankine cycle, we confirmed MS solution provide between 0.5-1% higher plant efficiencies, see Table 7 and 8 results in comparison with Table 9 and 10 results.

Table 9. Comparison between Subcritical Rankine power cycle and Supercritical Rankine power cycle design-point performance in a LF with MS solar power plant, *(550 ºC HP inlet).*

Power cycle	**subcritical Water (reference)**	**subcritical Water (reference)**	**supercritical Water**	**supercritical Water**	**supercritical Water**	**supercritical Water**
Graphical illustration	Figs. 1, 2	Figs. 1, 2	Fig. 4	Fig. 4	Fig. 4	Fig. 4
DRH stages	2^{nd}	1^{st}	2^{nd}	1^{st}, 2^{nd}, 3^{rd}	1^{st}, 2^{nd}	2^{nd}, 3^{rd}
SF pressure (bar)	104	104.5	15	15	15	15
HP inlet (bar)	87.7	87.7	260	260	260	260
Net Efficiency (%)	40.44	40.16	43.77	45.06	44.62	44.27
Unitary power (W/m2)	226.5	222.1	235.6	240	238.9	236.9

Table 10. Comparison between Subcritical Rankine power cycle and Supercritical Rankine power cycle design-point performance in a PTC with MS solar power plant, *(550 ºC HP inlet).*

Power cycle	**Subcritical Water (reference)**	**Subcritical Water (reference)**	**Supercritical Water**	**Supercritical Water**	**Supercritical Water**	**Supercritical Water**
Graphical illustration	Figs. 1, 2	Figs. 1, 2	Fig. 4	Fig. 4	Fig. 4	Fig. 4
DRH stages	2^{nd}	1^{st}	2^{nd}	1^{st}, 2^{nd}, 3^{rd}	1^{st}, 2^{nd}	2^{nd}, 3^{rd}
SF pressure (bar)	104.6	104.7	15	15	15	15
HP inlet (bar)	87.7	87.7	260	260	260	260
Net Efficiency (%)	40.41	40.09	43.82	44.72	44.39	43.82
Unitary power (W/m2)	265.8	263.7	274.7	277	276.2	273.4

7. Conclusion

Line-focus solar power plant with Supercritical Rankine power cycles provides higher net plant efficiency up to 43-45% in comparison with Subcritical Rankine power plant, providing up to ~40% net plant efficiency, see simulations results in Tables 7 to 10. Seven feed-water pre-heaters and two or even three direct reheating stages are main advantages in Supercritical Rankine solar power plants.

Supercritical turbines should be industrial developed for line-focus solar power plants with DSG and Supercritical Rankine power cycles, as proposed in [3].

It was demonstrated Hitec XL transfer fluid provides higher net plant efficiency than DSG, in Supercritical Rankine solar power plants, saving steam compressors energy consumption required in DSG plants. However DSG has no environmental impact either any heat tracing electrical consumes. For future works, thermal energy storage system will be integrated in the solar plants configurations studied in this paper.

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